Appendix B

Carbon Coefficients Used in This Report

This appendix presents the background and methodology for estimating the carbon coefficients of fossil fuels combusted in the United States. The carbon coefficient of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all carbon in the fuel is oxidized during combustion. Historically, the carbon coefficients used in earlier editions of this report were developed using methods first outlined in the EIA report, *Emissions of Greenhouse Gases in the United States: 1987 – 1992*. The carbon coefficients in that report were developed to replace, in part, the more general coefficients originally developed by Marland and Pippin and subsequently adopted by the Intergovernmental Panel on Climate Change (IPCC).[1] The IPCC coefficients were intended to be suitable for all countries, and to support the division of petroleum consumption into the products defined by the International Energy Agency (IEA). Because U.S. fuels sometimes differ in composition from those used abroad and EIA divides petroleum product consumption into more than 20 different categories, rather than the six described by the IEA, the development of U.S. specific carbon coefficients improved the precision of U.S. carbon emission estimates.

This appendix provides a detailed list of methods and data sources for estimating the carbon coefficients of coal (by consuming sector), natural gas (broken into pipeline-quality and flared gas), and petroleum products. Though the methods for estimating carbon contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because carbon coefficients are presented in terms of mass/unit-energy (i.e., million metric tons carbon per quadrillion Btu or MMTC/Qbtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Next, carbon contents are derived from fuel sample data, using descriptive statistics to estimate the carbon share of the fuel by weight. Finally, the heat content of the fuel is then estimated based on the sample data, or where sample data is unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A summary of carbon coefficients used in this report appears in Table B1.

Table B1. Carbon Coefficients Used in this Report
(Million Metric Tons Carbon per Quadrillion Btu)

Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Coal												
Coal (Residential)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04[p]
Coal (Commercial)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04[p]
Coal (Industrial Coking)	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63[p]
Coal (Industrial Other)	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74[p]
Coal (Electric Utility)	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98[p]
Natural Gas												
Natural Gas (Pipeline)	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Natural Gas (Flared)	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Petroleum												
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19	20.23	20.29
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33	19.33	19.33
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99	16.99	16.99
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.33	19.33	19.34	19.34
Petrochemical Feed.	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Waxes	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81

Note: All coefficients based on Heating (Gross Calorific) Value and assume 100% combustion
[p]=Preliminary
Source: Estimates described in this Appendix

[1]G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol.14 (1990), pp. 319-336, and Intergovernmental Panel on Climate Change, Estimation of Greenhouse Gases and Sinks (1991), p. 2.18.

This appendix also supplies a detailed discussion of each fuel and its derived carbon coefficient below. The discussion begins with the carbon contents of coal because about one third of all U.S. carbon emissions from fossil fuel combustion are associated with coal consumption. The estimated carbon coefficients of coal have been revised this year to reflect the composition of a new set of coal samples from the U.S. Geological Survey, Coal Quality Database Version 2.0. This appendix then discusses the methods and sources for estimating the carbon content of natural gas. About one fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this appendix examines carbon contents of petroleum products. There are more than 20 different petroleum products accounted for in U.S. energy consumption statistics.

Coal

Approximately one-third of all U.S. carbon dioxide emissions from fossil fuel combustion are associated with coal consumption. Because the EIA collects coal consumption data by consuming sector, EIA adopted carbon coefficients by consuming sector. Because the carbon content of coal varies by the state in which it was mined and by coal rank, and the sources of coal for each consuming sector vary by year, the weighted average carbon coefficient for coal combusted in each consuming sector also varies over time. A time-series of carbon coefficients by coal rank and consuming sector appears in Table A1-2. Since the IPCC guidelines provide carbon coefficients by rank, EIA also adopted carbon coefficients by rank for comparison with other nations carbon coefficients.

Table B2. Carbon Coefficients for Coal by Consuming Sector and Coal Rank, 1990 - 2001
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Electric Power	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98[p]
Industrial Coking	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63[p]
Other Industrial	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74[p]
	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04[p]
Residential/Commercial												
Coal Rank												
Anthracite	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26[p]
Bituminous	25.43	25.45	25.44	25.45	25.46	25.47	25.47	25.48	25.47	25.48	25.49	25.49[p]
Sub-bituminous	26.50	26.49	26.49	26.48	26.49	26.49	26.49	26.49	26.49	26.49	26.48	26.48[p]
Lignite	26.19	26.21	26.22	26.21	26.24	26.22	26.17	26.20	26.23	26.26	26.30	26.30[p]

[p]=Preliminary

Sources: U.S. Geological Survey, US Coal Quality Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

Estimation Methods

Carbon coefficients are estimated on the basis of 6,588 coal samples collected by the US Geological Survey between 1973 and 1989. These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and carbon content of the coal samples are calculated. Dividing the carbon content (reported in pounds carbon dioxide) by the heat content (reported in million Btu) yields an average carbon coefficient. This coefficient is then converted into units of million metric tons per quadrillion Btu.

U.S. energy statistics provide data on the origin of coal used in four areas: 1) the electric power industry 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors. Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Sectoral carbon coefficients are then calculated by multiplying the share of coal purchased from each state by rank by the carbon coefficient estimated above. The resulting partial carbon coefficients are then totaled across all states and ranks to generate a national sectoral carbon coefficient.

Although not used to calculate emissions, national-level carbon contents by rank are more easily compared to carbon contents of other countries than are sectoral carbon contents. State-level carbon coefficients by rank developed above are weighted by overall coal production by state and rank (consumption by rank is unavailable in U.S. energy statistics) to support this comparison. Each state-level carbon coefficient by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial carbon coefficients are then summed across all states to generate an overall carbon coefficient for each rank.

The estimates of carbon coefficients for coal were updated and revised in 2002. The methodology employed for these estimates was unchanged from previous years, however, the underlying coal data sample set was updated. Previously, a set of 5,426 coal samples from the EIA coal analysis file were used to develop carbon content estimates. The results from that sample set appear below in Table B3. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained at numerous coal seams throughout the United States. Many of the samples were collected as early as the 1940s and 1950s, with sample collection continuing until the 1980s. The updated sample set included 6,588 coal samples collected by the U.S. Geological Survey between 1973 and 1989.

Table B3. 1990–2000 Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Electric Power	25.68	25.69	25.69	26.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.59	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Residential/ Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
Coal Rank											
Anthracite	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13
Bituminous	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
Sub-bituminous	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
Lignite	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62

Sources: Emission factors by consuming sector from B.D. Hong and E.R. Slatick, “Carbon Dioxide Emission Factors for Coal,” U.S. Energy Information Administration, *Quarterly Coal Report, January-March 1994*. (Washington, DC, 1994) and emission factors by rank from Science Applications International Corporation, “Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report,” prepared for the U.S. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

Data Sources

Ultimate analyses of 6,588 coal samples were obtained from the U.S. Geological Survey, CoalQual Database Version 2.0 (1998). Data contained in the CoalQual Database are largely derived from samples taken between 1973 and 1989, and were largely reported on in State Geological Surveys.

Coal distribution by state and consumption by sector from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 10 and Table 63. Web site at www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

Coal production by state and rank from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 9. Web site at www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent carbon by weight and contains 14.2 million metric tons carbon per quadrillion Btu (Higher Heating Value), but it may also contain many other compounds that can lower or raise its overall carbon content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs) and 2) non-hydrocarbon gases. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. NGLs have a commercial value greater than that of methane, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline[2] contributes to the gasoline/naphtha "octane pool" used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as carbon dioxide, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline

[2]A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

specifications. Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared contains NGLs and carbon dioxide, it will typically have a higher overall carbon content than gas that has been processed and moved to end-use customers via transmission and distribution pipeline.

Estimation Methods

In the United States, pipeline-quality natural gas is expected to have an energy content greater than 970 Btu per cubic foot but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent methane, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which perhaps 1 percent is carbon dioxide.

However, there is a range of gas compositions that are consistent with pipeline specifications. The minimum carbon coefficient for natural gas would match that for pure methane, which equals1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher carbon emissions factors, because the "low" Btu gas has a higher content of inert gases (including carbon dioxide offset with more NGLs), while "high" Btu gas tends to have more NGLs.

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.

- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

A relationship between carbon content and heat content may be used to develop a carbon coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (and therefore carbon contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. To demonstrate that these samples were representative of actual natural gas "as consumed" in the US, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the U.S. was 1,025 Btu per cubic foot, varying by less than 1 percent (1,025 to 1,031 Btu per cubic foot) over the past 5 years. Meanwhile the average heat content of the 6,743 samples was 1,027 Btu per cubic foot and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the U.S. The average and median composition of these samples appears in Table B4.

Table B4. Composition of Natural Gas
(Percent)

Compound	Average	Median
Methane	93.07	95.00
Ethane	3.21	2.79
Propane	0.59	0.48
Higher Hydrocarbons	0.32	0.30
Non-hydrocarbons	2.81	1.43
Higher Heating Value (Btu per cubic foot)	1,027	1,032

Source: Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.*

Carbon coefficients were then calculated for eight separate sub-samples based on heat content and shown in Table B5.

Table B5. Carbon Content of Pipeline-Quality Natural Gas by Energy Content

Sample	Average Carbon Coefficient (Million Metric Tons per Quadrillion Btu)
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
Weighted National Average	14.47

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, DC, November, 1994,) Appendix A.

Because there is some regional variation in the energy content of natural gas consumed, a weighted national average carbon content was calculated using the average carbon contents for each sub-sample of gas that conformed with each individual state's typical cubic foot of natural gas. The result was a weighted national average of 14.47 million metric tons per quadrillion Btu. This was identical to the average carbon coefficient for all samples with more than 1,000 Btu per cubic foot and the average carbon coefficient for all samples with a heat content between 1,025 and 1,050 Btu per cubic foot. Because those samples with a heat content below 1,000 Btu had an unusually high carbon coefficient attributable to large portions of carbon dioxide (not seen in the median sample), they were excluded from the final sample so as not to bias the carbon coefficient upwards.

Selecting a carbon coefficient for flare gas was much more difficult than for pipeline natural gas because of the uncertainty of its composition. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average carbon coefficient for samples with more than 1,100 Btu per cubic foot, 14.92 million metric tons per quadrillion Btu, was adopted as the coefficient for flare gas. It should be noted that the sample data set did not include any samples with more than 1,130 Btu per cubic foot.

Data Sources

Natural gas samples were obtained from a Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.*

Average heat content of natural gas consumed in the U.S. from the Energy Information Administration, *Monthly Energy Review*, (Washington, DC), Table A4. Web site at www.eia.doe.gov/mer/txt/mer-a4.

Average heat content consumed on a state by state basis from the Energy Information Administration, *State Energy Data Report*, (Washington, DC), Table 1 and 2. Web site at www.eia.doe.gov/emeu/sedr/contents.html#PDF%20Files.

Petroleum

There are four critical determinants of the carbon coefficient for a petroleum-based fuel:

1. The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);
2. The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;
3. The specific types of 'families' of hydrocarbons that make up the hydrocarbon portion of the fuel; and
4. The heat content of the fuel.

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).[3] This is a range in density of 60 to 150 kilograms per barrel, or ±50 percent. The variation in carbon content, however, is much smaller (±5 to 7 percent): ethane is 80 percent carbon by weight, while petroleum coke is 90 to 92 percent carbon. The tightly bound range of carbon contents can be explained by basic petroleum chemistry.

Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and carbon in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of carbon atoms in each molecule. Petroleum products consisting of relatively simple molecules and few carbon atoms have low boiling temperatures and, larger molecules with more carbon atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater carbon content as well. Petroleum products with higher carbon contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with a lower carbon content. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and carbon and hydrogen content. Figure B1 compares carbon coefficients calculated on the basis of the derived formula with actual carbon coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

The derived empirical relationship between carbon content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Actual petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of carbon content.

Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the carbon content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

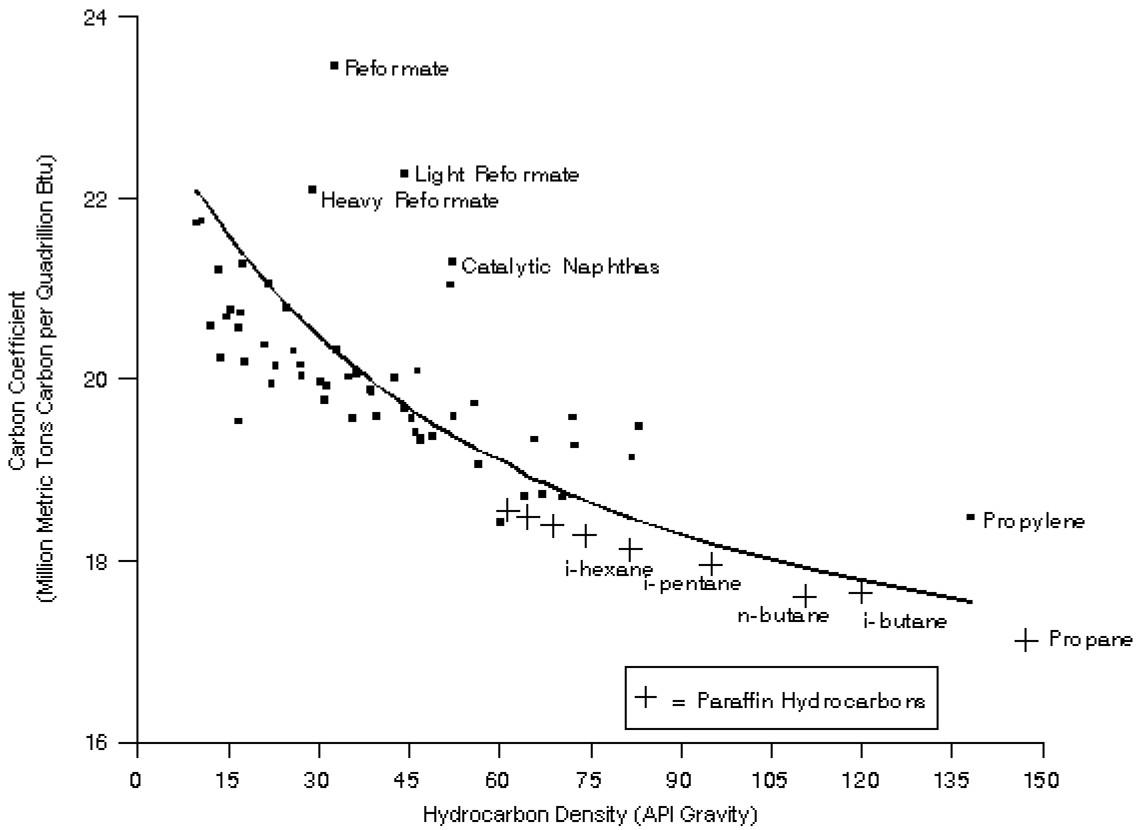
Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and carbon content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

Paraffins. Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula C_nH_{2n+2}. Paraffins include ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and octane (C_8H_{18}). As the chemical formula suggests, the carbon content of the paraffins increases with their carbon number: ethane is 80 percent carbon by weight, octane 84 percent. As the size of paraffin molecules increases, the carbon content approaches the limiting value of 85.7 percent asymptotically (See Figure B2).

[3] API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can by calculated with the following formula Degrees API =(141.5/Specific Gravity) – 131.5. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

Figure B1. Estimated and Actual Relationships Between Petroleum Carbon Coefficients and Hydrocarbon Density



Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, "Calculating Heating Values from the Elemental Composition of Fossil Fuels,' *Fuel,* Vol. 58 (January 1979), p.69.

Cycloparaffins. Cycloparaffins are similar to paraffins, except that the carbon molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula C_nH_{2n} and are 85.7 percent carbon by mass, regardless of molecular size.

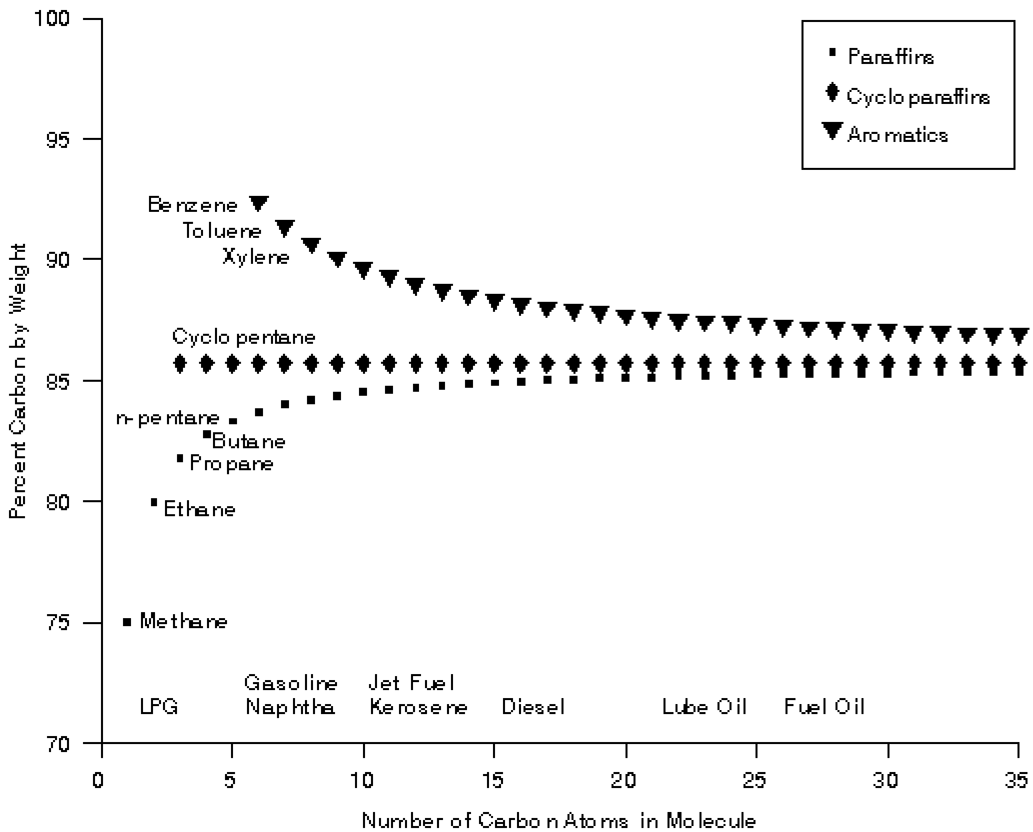
Olefins. Olefins are a reactive and unstable form of paraffin: a straight chain with the two hydrogen atoms at each end of the chain missing. They are never found in crude oil but are created in moderate quantities by the refining process. Thus, gasoline, for example, may contain 2 percent olefins. They also have the general formula C_nH_{2n}, and hence are also always 85.7 percent carbon by weight. Propylene (C_3H_6), a common intermediate petrochemical product, is an olefin.

Aromatics. Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by steam reforming of naphtha. Aromatics also take the form of ring structures with some double bonds between carbon atoms. The most common aromatics are benzene (C_6H_6), toluene (C_7H_8), and xylene (C_8H_{10}). The general formula for aromatics is C_nH_{2n-6}. Benzene is 92 percent carbon by mass, while xylene is 90.6 percent carbon by mass. Unlike the other hydrocarbon families, the carbon content of aromatics declines asymptotically toward 85.7 percent with increasing carbon number and density. (See Figure B2)

Polynuclear Aromatics. Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_2$ and 94.4 percent carbon by mass) and anthracene ($C_{14}H_4$ and 97.7 percent carbon). They are relatively rare but do appear in heavier petroleum products.

Figure B2 illustrates the share of carbon by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 carbon atoms are all natural gas liquids; hydrocarbons with 5 to 10 carbon atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 carbons comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules are generally used as lubricants, waxes, and residual fuel oil.

Figure B2. Carbon Content of Pure Hydrocarbons as a Function of Carbon Number



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent carbon by mass is not an unreasonable first approximation. Since denser products have higher carbon numbers, this guess would be most likely to be correct for crude oils and fuel oils. The carbon content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

Individual Petroleum Products

The U.S. maintains data on the consumption of more than 20 separate petroleum products and product categories. The carbon contents, heat contents, and density for each product are provided below in Table B6. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table B6. Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2001 Carbon Content (MMTC/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.34	5.253	59.6	86.60
LPG	16.99	*	*	*
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248[a]	67.1 [a]	84.11 [a]
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.29	5.800	30.5	85.49
Unfinished Oils	20.29	5.825	30.5	85.49
Miscellaneous Products	20.29	5.796	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	18.24	4.620	81.7	83.70

[a]Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.
* LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and carbon content, see table B9.
-(No sample data available)
Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, Washington, DC, (November, 1994), DOE/EIA 0573

Motor Gasoline and Motor Gasoline Blending Components

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.[4] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. carbon dioxide emissions. EIA collects consumption data (i.e., "petroleum products supplied" by wholesalers) for several types of gasoline: leaded regular, unleaded regular, and unleaded high octane. The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, which implies a range of possible carbon and energy contents per barrel. Table B7 reflects changes in the density of gasoline over time and across grades of gasoline through 2001.

[4]Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

Table B7. Motor Gasoline Density, 1990 – 2001
(Degrees API)

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Winter Grade												
Low Octane	62.0	61.8	61.4	61.0	60.1	59.8	60.6	61.5	61.8	61.6	61.6	61.7
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	61.2	61.3	61.2	61.2
High Octane	59.0	59.3	59.0	58.7	58.5	58.0	58.5	59.3	60.0	60.3	59.7	59.1
Summer Grade												
Low Octane	58.2	58.0	57.4	56.1	55.7	56.1	56.9	57.1	57.6	57.7	56.8	57.2
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7	57.4	58.0	58.0
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7	57.4	55.8	55.5

Source: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline Winter* (1990-2001).

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the "anti-knock" quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. In reformulated gasoline, methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME) are often added to standard gasoline to boost it oxygen content. The increased oxygen reduces the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in carbon than standard gasoline. The average gallon of reformulated gasoline consumed in 2001 contained 8 percent MTBE and 0.5 percent TAME. The characteristics of reformulated fuel additives appear in Table B8.

Table B8. Characteristics of Major Reformulated Fuel Additives

Additive	**Density** (Degrees API)	**Carbon Share** (Percent)	**Carbon Content** (MMTC/Qbtu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Source: American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

Estimation Methods

U.S. gasoline consumption was divided by product grade and season for both standard gasoline and reformulated gasoline. Carbon coefficients for each grade and type are derived from three parameters: gasoline density, share of the gasoline mixture that is carbon; and the energy content of a gallon of gasoline. Carbon coefficients for reformulated fuels were calculated by applying the carbon coefficient for the fuel additives listed in Table B8 to the increased share of reformulated gasoline represented by these additives (standard gasoline contains small amounts of MTBE and TAME) and weighting the gasoline carbon content accordingly. The carbon content for each grade and type of fuel is multiplied by the share of overall consumption that the grade and fuel type represent. Individual coefficients are then summed to yield an overall carbon content coefficient.

The carbon coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of carbon coefficients for motor gasoline. This change resulted in a downward step function in carbon coefficients for gasoline of approximately 0.3 percent beginning in 1995.

Data Sources

The density of motor gasoline is drawn from the National Institute for Petroleum and Energy Research, *Motor Gasolines, Summer* (various years) and the National Institute for Petroleum and Energy Research, *Motor Gasolines, Winter* (various years).

The characteristics of reformulated gasoline additives is taken from American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

The carbon content of motor gasoline is found in Mark DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993), Appendix C, pp. C-1 to C-8 and ultimate analyses of one sample of shale-oil derived gasoline from Applied Systems Corp., *Compilation of Oil Shale Test Results* (Submitted to the Office of Naval Research, April 1976), p. 3-2, three varieties of gasoline from C.C. Ward, "Petroleum and Other liquid Fuels," in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14, and one sample of gasoline from J.W. Rose and J.R. Cooper, *Technical Data on Fuel,* The British National Committee, World Energy Conference, London, England (1977).

Standard heat contents for motor gasoline of 5.253 million Btu per barrel conventional gasoline and 5.150 million Btu per barrel reformulated gasoline were adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the U.S.: "naphtha-based" jet fuels and "kerosene-based" jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The carbon coefficient for jet fuel used in this report represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients.

Estimation Methods

Because naphtha-based jet fuel is used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 million Btu per barrel based on EIA industry standards. The carbon fraction was derived from an estimated hydrogen content of 14.1 percent and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.[5]

The density and carbon share of kerosene-based jet fuels was based on the average composition of 39 fuel samples taken by Boeing Corporation (the leading U.S. commercial airline manufacturer) in 1989. The EIA's standard heat content of 5.67 million Btu per barrel was adopted for kerosene-based jet fuel.

The carbon content for each jet fuel type is multiplied by the share of overall consumption of that fuel type. Individual coefficients are then summed to yield an overall carbon coefficient.

Between 1994 and 1995, the carbon coefficient for kerosene-based jet fuel was revised downward from 19.71 million metric tons per quadrillion Btu to 19.33 million metric tons per quadrillion Btu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenthy in 1990. The latter set of fuel samples have a decreased density and slightly lower carbon share than the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and thus, probably yields a downward bias in the revised carbon coefficient.

Data Sources

The carbon content of naphtha-based jet fuel is from C.R. Martel and L.C. Angello, "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," in *Current Research in Petroleum Fuels,* Volume I (New York, NY: MSS Information Company, 1977), p. 116.

[5]Martel, C.R., and Angelo, L.C. Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels. Current Research in Petroleum Fuels. Vol. I. New York, NY: MSS Information Corporation, 1977.

The density of naphtha-based jet fuel is from the American Society for Testing and Materials*, ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985), p. 60.

A standard heat content for naphtha-based jet fuel was adopted from the U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Available online at: www.eia.doe.gov/emeu/aer/contents.html.

Carbon content and density for kerosene-based jet fuels is drawn from O.J. Hadaller and A.M. Momenthy, *The Characteristics of Future Fuels,* Part 1, "Conventional Heat Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50.

A standard heat content for kerosene-based jet fuel was adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/ contents.html.

Distillate Fuel

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Estimation Methods

For the purposes of this report, the carbon content of No. 2 fuel oil is assumed to typify the carbon content of distillate fuel generally. The carbon share in No. 2 fuel oil was estimated based on the average of 11 ultimate analyses. This carbon share was combined with EIA's standard heat content of 5.825 million Btu per barrel and the density of distillate assumed to be 35.5 degrees API, in accord with its heat content.

Data Sources

Carbon content and density were derived from the following:

- Four samples of distillate from C. T. Hare and R.L. Bradow, "Characterization of Heavy-Duty Diesel Gaseous and Particulate Emissions, and the Effects of Fuel Composition," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128;

- Three samples from E.F. Funkenbush, D.G. Leddy, and J.H. Johnson, "The Organization of the Soluble Organic Fraction of Diesel Particulate Matter," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979) p. 128;

- One sample from R.L. Mason, "Developing Prediction Equations for Fuels and Lubricants," SAE Paper 811218, p.34;

- One sample from C.T. Hare, K.J. Springer, and R.L. Bradow, "Fuel and Additive Effects on Diesel Particulate- Development and Demonstration of Methodology," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 179; and

- One Sample from F. Black and L. High, "Methodology for Determining Particulate and Gaseous Diesel Emissions," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128.

A standard heat content was adopted from the Energy Information Administration *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Residual Fuel

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about a third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No.6 fuel oil) consumed by electric utilities has an energy content of 6.287 million Btu per barrel and an average sulfur content of 1 percent.[6] This implies a density of about 17 degrees API.

Estimation Methods

For this report, residual fuel was defined as No.6 fuel oil. The National Institute of Petroleum and Energy Research, Fuel Oil Survey shows an average density for fuel oil of 11.3 API gravity and anecdotal evidence suggests that marine residual fuel is also very dense, with typical gravity of 10.5 to 11.5 degrees API.[7] Because the largest share of fuel oil consumption is for marine vessels, a density of 11 degrees API was adopted when developing the carbon coefficient for this report. An average share of carbon in residual fuel of 85.67 percent by mass was used based on ultimate analyses of a dozen samples.

Data Sources

The carbon content of residual fuel oil is based on the following:

- Three samples of residual fuel from the Middle East and one sample from Texas in F. Mosby, G.B. Hoekstra, T.A. Kleinhenz, and J.M. Sokra, “Pilot Plant Proves Resid Process,” in *Chemistry of Petroleum Processing and Extraction* (MSS Information Corporation, 1976), p.227;

- Three samples of heavy fuel oils from J.P. Longwell, “Interface Between Fuels and Combustion,” in *Fossil Fuel Combustion: A Sourcebook* (New York, NY: John Wiley & Sons, 1991);

- Three samples of heavy fuel oils from C.C. Ward, “Petroleum and Other Liquid Fuels,” in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14;

- Two samples of heavy fuel oils from, D.A. Vorum, “Fuel and Synthesis Gases from Gaseous and Liquid Hydrocarbons,” in American Gas Association, *Gas Engineer's Handbook* (New York, NY: Industrial Press, 1974), p. 3/71; and

- One sample of heavy fuel oil from W. Rose and J.R. Cooper, *Technical Data on Fuel,* The British National Committee, World Energy Conference, London, England (1977).

The density of residual fuel consumed for electric power generation is fromEnergy Information Administration, *Cost and Quality of Fuels*, (Washington, DC). Web site www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.

Density of residual fuel consumed in marine vessels from Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products,* (unpublished manuscript, April 1993) and the National Institute for Petroleum and Energy Research, *Fuel Oil Surveys* (Bartlesville, OK, 1992).

A standard heat content was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).Web site www.eia.doe.gov/emeu/aer/contents.html.

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[6]Energy Information Administration, Cost and Quality of Fuels, DOE/EIA-0191(Washington, DC). Available online at: www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.
[7]Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products,* (unpublished manuscript, April 1993)

Liquefied Petroleum Gases (LPG)

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (1). Thus, for example, the carbon share of propane, C_3H_8, is 81.8 percent. The densities and heat content of the compounds are also well known allowing carbon coefficients to be calculated directly. Table B9 summarizes the physical characteristic of LPG.

Table B9. Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Coefficient (MMTC/Qbtu)
Ethane	C_2H_6	16.88	80.0	2.916	16.25
Propane	C_3H_8	12.44	81.8	3.824	17.20
Isobutane	C_4H_{10}	11.20	82.8	4.162	17.75
n-butane	C_4H_{10}	10.79	82.8	4.328	17.72

Source: V.B. Guthrie (ed.), *Characteristics of Compounds*, Petroleum Products Handbook, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

Estimation Methods

Based on their known physical characteristics, a carbon coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases. A weighted carbon coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the preponderance of LPG consumed for fuel use is propane, the largest single LPG used for non-fuel applications is ethane. A carbon coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The changing shares of LPG fuel use and non-fuel use consumption appear below in Table B10.

Table B10. Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2001
(Million Metric Tons per Quadrillion Btu)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Consumption (Quads Fuel Use)												
Ethane	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.05	0.05	0.06	0.06	0.05
Propane	0.79	0.79	0.84	0.86	0.86	0.86	0.95	0.92	0.98	0.98	0.98	0.89
Butane	0.08	0.05	0.07	0.06	0.07	0.05	0.04	0.05	0.05	0.06	0.06	0.06
Total	0.90	0.85	0.94	0.94	0.96	0.93	1.02	1.03	0.99	1.10	1.10	1.01
Carbon Coefficient	17.21	7.21	17.21	17.22	17.22	17.20	17.20	17.18	17.18	17.18	17.18	17.18
Consumption (Quads non-Fuel Use)												
Ethane	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.71	0.68	0.77	0.81	0.73
Propane	0.53	0.59	0.61	0.55	0.65	0.67	0.65	0.71	0.68	0.76	0.76	0.69
Butane	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.25	0.24	0.28	0.29	0.27
Total	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.67	1.60	1.81	1.86	1.69
Carbon Coefficient	16.83	16.84	16.84	16.80	16.88	16.87	16.86	16.88	16.87	16.88	16.87	16.88
Weighted Carbon Coefficient	**16.99**	**16.98**	**16.99**	**16.97**	**17.01**	**17.00**	**16.99**	**16.99**	**16.99**	**16.99**	**16.99**	**16.99**

Sources: Consumption of LPG from Energy Information Administration, Petroleum Supply Annual, various years. Non-fuel use of LPG from American Petroleum Institute, Natural Gas Liquids and Liquefied Refinery Gas Survey, various years.

The carbon coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus – assumed to have the characteristics of hexane – in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in carbon per unit of energy, its removal from the consumption mix lowered the carbon coefficient for LPG from 17.26 million metric tons per quadrillion Btu to 17.02 million metric tons per quadrillion Btu. In 1998, EIA began separating LPG consumption into two categories: energy use; and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the carbon coefficient for fuel use is about 2 percent higher than the coefficient for non-fuel use.

Data Sources

Carbon share, density and heat content of liquefied petroleum gases from V.B. Guthrie (ed.), Characteristics of Compounds, *Petroleum Products Handbook*, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

LPG consumtpiton from Energy Information Administration, *Petroleum Supply Annual*, (Washington, DC) various years. Web site www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.

Non-fuel use of LPG from American Petroleum Institute, Natural Gas Liquids and Liquefied Refinery Gas Survey, various years.

Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Estimation Methods

A carbon coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 million Btu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon. To estimate the share of carbon in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a carbon share of 85 percent and a carbon coefficient of 18.87 million metric tons per quadrillion Btu.

Data Sources

Fuel characteristics were taken from the American Society for Testing and Materials, ASTM and Other Specifications for Petroleum Products and Lubricants (Philadelphia, PA, 1985).

A standard heat content for aviation gas was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Still Gas

Still gas, or refinery gas is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

Estimation Methods

The EIA obtained data on four samples of still gas. Table B11 below shows the composition of those samples.

Table B11. Composition, Energy Content, and Carbon Coefficient for Four Samples of Still Gas

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Coefficient (MMTC/Qbtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Because gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks, EIA selected the carbon coefficient from the sample with the lowest hydrogen content as the representative value for still gas.

Data Sources

One still gas sample was drawn from American Gas Association, *Gas Engineer's Handbook,* (New York, NY: Industrial Press, 1974), pp. 3.71, and three still gas samples came from C.R. Guerra, K. Kelton, and D.C. Nielsen, Natural Gas Supplementation with Refinery Gases and Hydrogen," in Institute of Gas Technology, *New Fuels and Advances in Combustion Technologies* (Chicago, IL, June 1979).

Asphalt

Asphalt is used to pave roads. Because most of its carbon is retained in those roads, it is a small source of emissions. It is derived from a class of hydrocarbons called "asphaltenes," abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower carbon contents than other hydrocarbons.

Estimation Methods

Ultimate analyses of twelve samples of asphalts showed an average carbon content of 83.5 percent. The EIA standard heat content for asphalt of 6.636 million Btu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate a carbon coefficient of 20.62 million metric tons per quadrillion Btu.

Data Sources

A standard heat content for asphalt was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt is from American Society for Testing and Materials***,*** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Estimation Methods

The ASTM Petroleum Measurement Tables give the density of lubricants at 25.6 degrees API. Ultimate analysis of a single sample of motor oil yielded a carbon content of 85.8 percent. A standard heat content of 6.065 million Btu per barrel was adopted. These factors produce a carbon coefficient of 20.24 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000* (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt was adopted from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called "naphtha," and those with a boiling temperature 400 degrees Fahrenheit and above.

Estimation Methods

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), "straight-run" naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average carbon share of 84.11 percent and an average density of 67.1 degrees API gravity. The standard EIA heat content of 5.248 million Btu per barrel is used to estimate a carbon coefficient of 18.14 million metric tons per quadrillion Btu.

Petrochemical feedstocks with a boiling temperature greater than 401 degrees Fahrenheit are part of the "middle distillate" fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel. Thus, the carbon coefficient of 19.95 million metric tons per quadrillion Btu used for distillate fuel is also adopted for this portion of petrochemical feedstocks. The weighted average of the two carbon coefficients for petroleum feedstocks equals 19.37 million metric tons per quadrillion Btu.

Data Sources

The carbon content and density of naphthas is estimated based on G.H. Unzelman, "A Sticky Point for Refiners: FCC Gasoline and the Complex Model," *Fuel Reformulation* (July/August 1992), p. 29.

A standard heat content for petrochemical feedstock was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

Kerosene

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 fuel oil.

Estimation Methods

The average density of 41.4 degrees API and average carbon share of 86.01 percent found in five ultimate analyses of No. 1 fuel oil samples were applied to a standard heat content of 5.67 million Btu per barrel to yield a carbon coefficient of 19.72 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Petroleum Coke

Petroleum coke is the solid residue of the extensive processing of crude oil. It is a coal-like solid, usually with a carbon content greater than 90 percent, that is used as a boiler fuel and industrial raw material.

Estimation Methods

Ultimate analyses of two samples of petroleum coke showed an average carbon share of 92.3 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 million Btu per barrel assumed. Together, these factors produced an estimated carbon coefficient of 27.85 million metric tons per quadrillion Btu.

Data Sources

Carbon content for petroleum coke was estimated from two samples from S. W. Martin, "Petroleum Coke," in Virgil Guthrie (ed.), *Petroleum Processing Handbook* (New York, NY: McGraw-Hill, 1960), pp. 14-15. Density of petroleum coke adopted from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and carbon percentage, requiring the development of multiple coefficients.

Estimation Methods

Hexane is a pure paraffin containing 6 carbon atoms and 14 hydrogen atoms. Thus, it is 83.7 percent carbon. Its density is 76.6 degrees API or 5.649 pounds per gallon and its derived carbon coefficient is 17.17 million metric tons per quadrillion Btu. The other hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall, 1985). These assumptions, when combined with the relevant densities, yield the carbon coefficients contained in Table B12 below.

Table B12. Characteristics of Non-hexane Special Naphthas

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Content (Percent)	Carbon Coeficient (MMTC/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

EIA reports only a single consumption figure for special naphtha. The carbon coefficients of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane and the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.86 million metric tons carbon per quadrillion Btu.

Data Sources

A standard heat content for special naphtha was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

Density and aromatic contents for special naphthas are from K. Boldt and B.R. Hall, *Significance of Tests for Petroleum Products* (Philadelphia, PA: American Society for Testing and Materials), p. 30.

Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of carbon atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer carbon chains and more variation in their chemical bonds than paraffin waxes.

Estimation Methods

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 carbon atoms. The resulting carbon share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 carbon atoms, yielding a carbon share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

A weighted average density and carbon coefficient was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average carbon content is 85.29 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 million Btu per barrel. These inputs yield a carbon coefficient for petroleum waxes of 19.81 million metric tons per quadrillion Btu.

Data Sources

The density of paraffin wax is from American Society for Testing and Materials***,*** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). The density of microcrystalline waxes is based on 10 samples found in V. Guthrie (ed.), *Petroleum Products Handbook* (New York, NY: McGraw-Hill, 1960).

A standard heat content for petroleum waxes was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

Crude Oil, Unfinished Oils, and Miscellaneous

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption and unfinished oils are a balancing item that may show negative consumption. For carbon accounting purposes, it was assumed that all these products have the same carbon content as crude oil.

Estimation Methods

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating carbon content based on this information, ultimate analyses of 182 crude oil samples were collected. Within the sample set, carbon content ranged from 82 to 88 percent carbon, but almost all samples fell between 84 percent and 86 percent carbon. The density and sulfur content of the crude oil data were regressed on the carbon content, producing the following equation:

$$\textit{Percent Carbon} = 76.99 + (10.19 * \textit{Specific Gravity}) + (-0.76 * \textit{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.[8] When carbon content was adjusted to exclude sulfur, the R-squared rose to 0.65. While sulfur is the most important nonhydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur

[8] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

content. Restating these results, density accounts for about 35 percent of the variation in carbon content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2001 crude oil quality data (30.49 degrees API and 1.42 percent sulfur) produces an estimated carbon content of 85.81 percent. Applying the density and carbon content to the EIA standard energy content for crude oil of 5.8 million Btu per barrel produces an emissions coefficient of 20.29 million metric tons per quadrillion Btu.

Data Sources

The carbon content for crude oil was developed from an equation based on 182 crude oil samples, including 150 samples from U.S. National Research Council, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* (New York, NY: McGraw-Hill, 1927).

A standard heat content for crude oil was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).). Web site.eia.doe.gov/emeu/aer/contents.html.